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Sub-Threshold J/ψ Meson Photo-Production

Submitted by

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Abstract

We propose to measure the nuclear dependence of sub-threshold J/ψ photo-production to extract the physical J/ψ-N cross section. It is unclear whether the previous experiments have measured this cross section, since at their higher energies the J/ψ may have formed outside the nucleus. Theory predicts a larger cross section than the experimental determinations. A measurement of this quantity may help to understand the $c\bar{c}$ formation to a hadronic state and the strength of the QCD van der Waals potential. Furthermore, the physical J/ψ-N cross section is important in the interpretation of relativistic heavy ion collision data.

Introduction

With the advent of higher energies at Jefferson Lab, the study of charmonium becomes possible. The threshold production of J/ψ meson photo-production on hydrogen is ~ 8.2 GeV, but by scattering off high momentum components of the nucleus one can reach the threshold energies needed for charmonium production at lower photon energies. Threshold charm production on a nucleus can give information on the J/ψ-N interaction, which is important in understanding the actual strength of the QCD van der Waals potential due to gluon exchange between the meson and nucleon [1] [2] [3]. Additionally, knowledge of the propagation of the J/ψ's in nuclei is relevant to the interpretation of relativistic heavy ion collisions, since it is believed that J/ψ suppression maybe a signal for the formation of quark-qluon plasma [4]. The standard method to extract this quantity has been to measure the nuclear dependence of J/ψ production. The majority of these A-dependent J/ψ production experiments have been measured at high energy, while the only near-threshold experiment was performed using 20 GeV photons. This 20 GeV SLAC experiment measured $\sigma_{J/\psi N} = 3.6 \pm 0.8 \pm 0.5$ mb[5]; whereas theory predicts this cross section to be higher, about 7 mb [3]. It is unclear whether the SLAC determination of $\sigma_{J/\psi N}$ corresponds to the physical $\sigma_{J/\psi N}$, due to the fact that at these energies the J/ψ may still be formed outside the nucleus [6] [7]. A measurement of the nuclear dependence of sub-threshold J/ψ photo-production may resolve this issue. To boost the count rates, the experimental technique will be to use the target as a bremsstrahlung radiator. The J/ψ mesons will be tagged via their decay to $\mu^+\mu^-$.

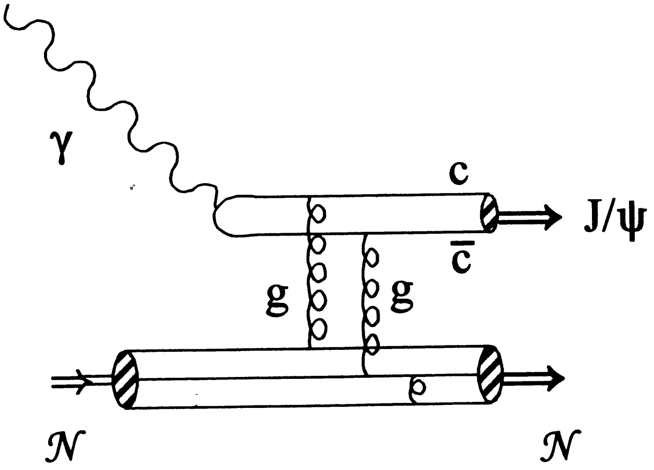

Figure 1 Quasi-elastic production

Motivation

The production mechanism of J/ψ mesons from nuclei can be split up into three processes, coherent elastic, quasi-elastic, and inelastic scattering. In coherent production, the photon fluctuates to an off-shell $c\bar{c}$ pair which scatters elastically from the nucleus. In the quasi-elastic reaction, the $c\bar{c}$ pair scatters elastically off a nucleon in the nucleus. At threshold, t_{min} is about 1 GeV, hence coherent production can be neglected and the dominating process is quasi-elastic production. The leading-order elastic contribution is two qluon exchange as shown in Figure 2 [3]. Inelastic scattering is believed to be described by the photon-gluon fusion mechanism [8], where the photon interacts with the gluon content of the nucleon through the sub-process, $\gamma g \rightarrow c\bar{c}$.

Following the convention of Brodsky and Mueller [6], the interaction is split into two time scales, production time (τ_P) and formation time (τ_F). In the target rest frame, the production time is the time of the hard interaction while the formation time is the time that the produced partonic system takes to reach the physical configuration of the hadron. The production time or, as it is sometimes called, the coherence time, has the following form in the target rest frame:

$$\tau_P \cong \frac{2\nu}{4m_c^2 + Q^2} \xrightarrow[Q^2=0]{} 0.02\,\nu \text{ fm GeV}^{-1} \tag{1}$$

✓ 0.04fm

This is the lifetime of the hadronic fluctuation and for energies below 150 GeV the interaction involves a single nucleon in the nucleus. The formation time according to Kopeliovich and Zakharov has the following form:

$$\tau_F \cong \frac{2}{m_{\psi'} - m_{J/\psi}} \left[\frac{E_{J/\psi}}{2m_c} \right] \cong 0.2\,\nu \text{ fm GeV}^{-1} \tag{2}$$

where ν is the photon energy and is approximately equal to the J/ψ energy since for elastic scattering $z = E_{J/\psi}/\nu$ is close to one. There seems to be some disagreement between various authors about the size of the formation time [1] [9] [10], but all draw the same conclusion if the formation time is less than the size of the nucleus. This view is that the Vector Meson Dominance/Glauber prediction shown below is valid for $\tau_F \ll R_A$ where R_A is the radius of the nucleus.

$$T_N(A) \cong 1 - \frac{1}{2A}\sigma_{J/\psi N} \int d^2b\, T(b)^2 \tag{3}$$

where $T_N(A) = \sigma_A / A\sigma_A$ is the transparency factor and $T(b)$ and b are the optical thickness of the nuclei and the impact parameter. Thus one can measure the transparency factor on two nuclear targets and form a ratio to extract the J/ψ-N cross section.

$$\frac{\sigma_{A_1}}{\sigma_{A_2}} = \frac{T_N(A_1)}{T_N(A_2)} \cdot \frac{A_2}{A_1} \tag{4}$$

Forming this ratio enables the extraction of $\sigma_{J/\psi N}$ without measuring absolute cross sections. Since there is a large uncertainty in the formation time, it is advantageous to measure J/ψ production with a low energy probe, hence maximizing the chance that the $c\bar{c}$ forms into a J/ψ within the nucleus. As an example, using the formation time from Equation 2, the J/ψ's produced in the SLAC near-threshold experiment would have a formation time of 4 fm. While this is consistent with the typical nuclear size, it is unclear whether the application of the Glauber model is valid.

A $c\bar{c}$ state is thought to interact with a nucleon or nucleus through multiple gluon exchange, since valence quark exchange is not possible in QCD. This multiple gluon exchange behaves similar to a (color) van der Waals interaction. Luke, Manohar, and Savage have shown that in the limit where the inverse radius, $r_Q^{-1} \sim \alpha_s(r_Q^{-1})m_Q$, of the $Q\bar{Q}$ bound state is larger than the QCD scale Λ_{QCD}, the process can be determined directly from the operator product expansion [11]. Furthermore, it has been established that hadron corrections to the J/ψ-N interaction are negligible[3]. Consequently, a measurement of the J/ψ-N interaction may provide information on the actual strength of this (color) van der Waals potential.

There is some thought that the large spin-spin correlation A_{NN} observed in *pp* elastic scattering [12] near the charm threshold may be a signal of strong $c\bar{c}$ interactions with nucleons [13]. Using the arguments from Ref. [13], de Téramond, Espinoza, and Ortega-Rodríguez have determined that a value of the J/ψ-N cross section equal to about 5 mb could explain the anomalous spin-spin correlation [14]. Since a van der Waals force is attractive, there is a possibility of nuclear bound quarkonium [1][11][15]. Although the J/ψ's produced in this experiment will have rather large momentum and will not likely form a bound state with the nucleus, this experiment seeks to verify whether the physical J/ψ-N cross section is indeed larger than previous experiments found, thus allowing for such an effect.

Another interesting application of the J/ψ-N cross section is in the interpretation of relativistic heavy ion collisions. It is thought that a signature for the formation of a quark-gluon plasma is J/ψ suppression [4][16]. The belief is that at sufficiently high parton densities there will be deconfinement which leads to an average gluon momentum that is five times higher than in a confined medium [17]. Since the dominant break up process for a J/ψ is through the exchange of hard gluons, one would expect J/ψ suppression in deconfined matter. To be able to distinguish J/ψ production between confined and deconfined matter requires understanding the propagation of fully formed J/ψ's in nuclear matter[18].

Kinematics

Since the photon energy, ν, must be above 8.21 GeV to produce J/ψ mesons on a hydrogen target, nuclear targets must be utilized for production below this energy. Here one relies on the high momentum components of the nuclei. Figure 2 shows the relationship between threshold photon energy and the nucleon antiparallel momentum component. As shown in Figure 2, there is enough energy for a 6 GeV photon to create a J/ψ if the nucleon has a momentum of about 365 MeV/c in the opposite direction to the photon. The nucleon needs about 180 MeV/c for a 7 GeV photon.

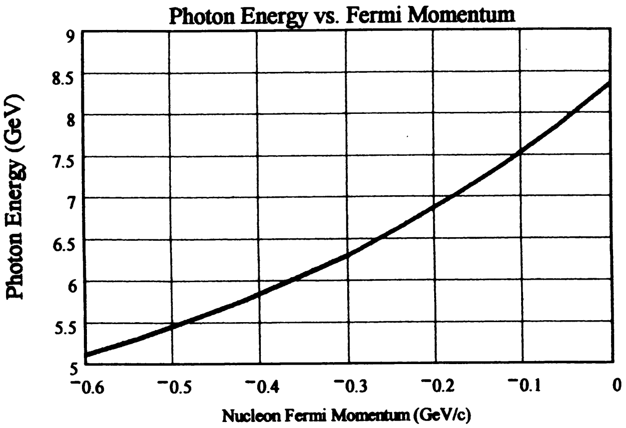

Figure 2 Threshold photon energy versus nucleon Fermi momentum (note: antiparallel component of momentum).

Figure 4 shows the nucleon momentum distribution for ^{12}C, ^{27}Al, ^{56}Fe, and nuclear matter[19]. Above 350 MeV/c the distributions for nuclei with $A \geq 4$ are believed to be very similar[20][21]. This is an advantage with regard to Equation 4. An obvious disadvantage is that the percentage of nucleons in the nucleus which have enough momentum to reach the threshold energy to production a J/ψ meson is small.

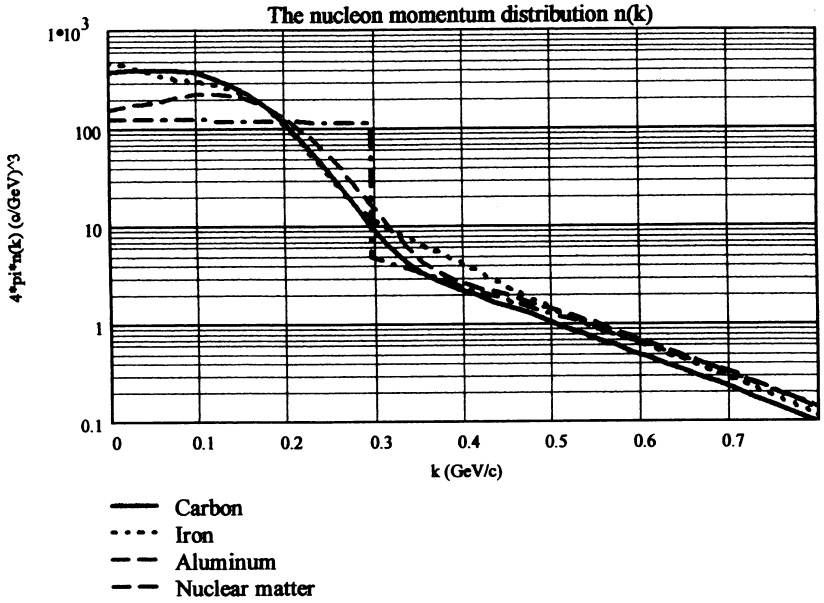

Figure 3 Nucleon momentum distribution for ^{12}C, ^{27}Al, ^{56}Fe, and nuclear matter. The normalization is $\int n(k) \cdot k^2 \cdot dk = 1$

Production Mechanism

The dominant production mechanism at threshold is quasi-elastic scattering of a single nucleon. Here the photon fluctuates to an off-shell J/ψ meson and scatters elastically from the nucleon. The Mandelstam variable $t = (q-p_{J/\psi})^2 = (p-p')^2$ is the momentum transfer to the target. At 6 GeV, t_{min}, the minimum momentum transfer, equals about 1 GeV. Therefore, the nuclear form factor is very suppressed and one does not expect much contribution from coherent elastic scattering from the nucleus. At threshold, inelastic scattering is suppressed due to phase space considerations. In addition, separation of the elastic and inelastic processes can be carried out by using cuts on the kinematical variables z and P_T^2.

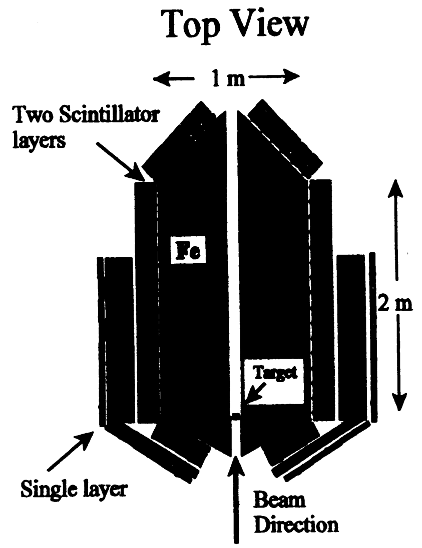

Figure 4 Top view drawing of the experimental Setup.

Experimental Setup

Figure 4 shows the experimental setup. The idea is straightforward, look for μ pairs in coincidence from J/ψ decays. The target has a radiative length of about 10% and the photons are created via bremsstrahlung in the target. It has been calculated that the probability of creating a high energy photon in the target is ~ 1×10^{-3} for a 6 GeV electron. Surrounding the target will be a thick layer of iron to eliminate the hadronic background. This particular arrangement is to provide an increasing iron thickness, since forward going particles will have greater momentum. The average energy loss and the iron thickness versus θ are shown in Figures 5 and 6. There will be two layers of scintillators after the iron muon filter. The first scintillator layer is 1 cm thick while the second layer is 10 cm thick. The μ pair angular distribution is shown in fig 4. On both sides of the target there will be another layer of iron (~ 20 cm) and a layer of scintillators. These will be used to range out the lower p_T μ's at large θ coming from background processes and effectively measuring the energy of the μ. As shown in Figure 7 for J/ψ decays, a large angle μ is correlated with a forward angle μ. The μ's produced from J/ψ's have full angular coverage in θ^{Lab} since β_{μ} in the J/ψ rest frame will always be greater than $\beta_{J/\psi}$ at CEBAF energies. A J/ψ event will consist of a coincidence from all three scintillator layers of the large angle μ with a double coincidence of a forward angle μ. The angular coverage in θ^{Lab} is from 5° to 170° while the coverage in ϕ^{Lab} (out-of-plane angle) is $-45° \le \phi \le 45°$ and $135° \le \phi \le 225°$. Therefore the effective solid angle is close to 2π.

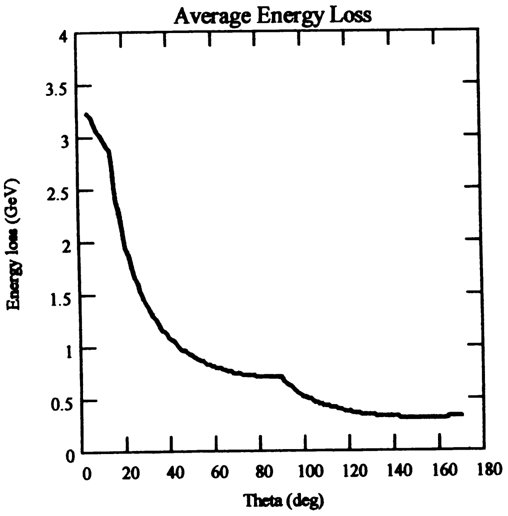

Figure 5 Average μ energy loss at ϕ = 0°

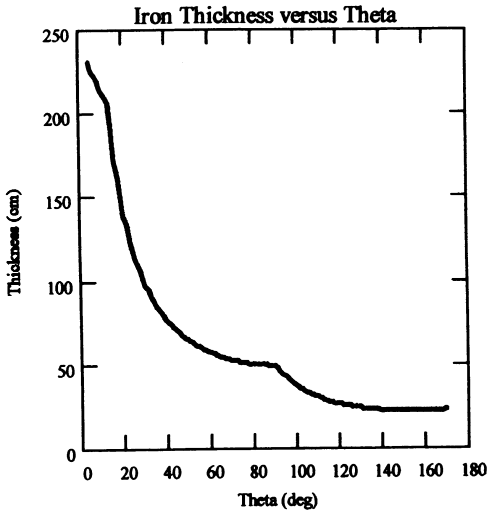

Figure 6 Iron Thickness at ϕ = 0°

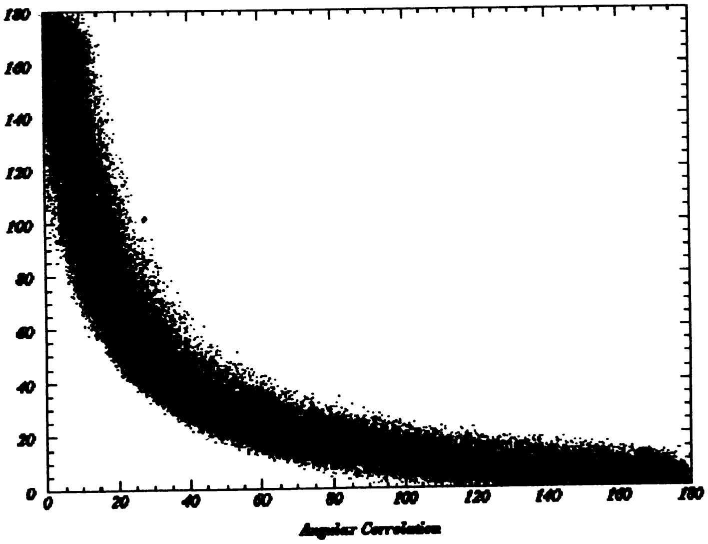

Figure 7 Lab angular correlation between the μ pair from J/ψ decays.

Background

The background can be separated into two types, coincidence and singles. The singles background will come from photons, neutrons, punch through pions and kaons, and pions and kaons which decay in flight. The photon and neutron singles will be reduced by requiring all layers of detectors to fire and should not affect the coincidence rate. The hadronic punch through and μ's from hadronic decays have been studied in a Geant simulation. The affect on the coincidence rate is negligible when folding in photo-production data from Wiser[22]. The main problematic background will come from μ pair from other processes, i.e. Bethe-Heitler and meson decays. The μ's from bremsstrahlung are in principle calculable and should not pose any real problem. Meson decays are another story, while the branching ratios to μ pairs is quite small, the cross sections relative to the J/ψ are quite large. In general, the product of the branching ratio to μ pairs and the cross section is about equal for the ρ, ω, ϕ, and J/ψ mesons. The real problem results from the fact that these lower mass mesons can use all the nucleons in the nucleus and a larger fraction of the photon spectrum. The elimination of these backgrounds can be done by a combination of cuts on the angular correlation between the μ pair and an energy cut on the large angle μ. As an example, the separation in the μ opening angle and momentum versus θ are shown in figures 8 and 9 for J/ψ and ρ decays. Note that the shielding configuration will induce an energy cutoff (see Figure 5) which matches the μ momentum distribution of Figure 9 very well. In addition, since the lower mass meson cross sections are flat above a few GeV, by lowering the beam energy and effectively turning off the J/ψ production, the contribution from the background can be measured.

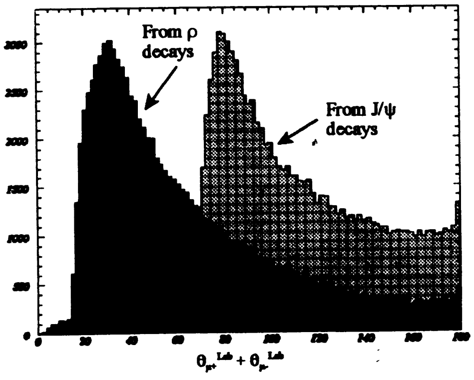

Figure 8 Opening angle of μ pair for J/ψ and ρ decays.

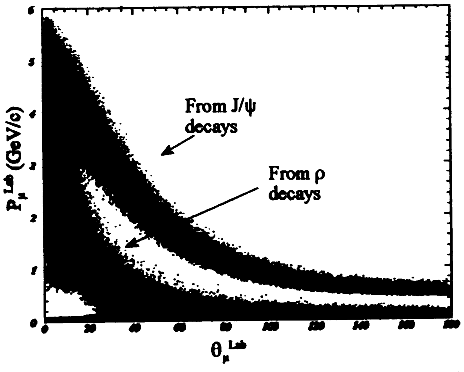

Figure 9 μ momentum distribution versus θ for J/ψ and ρ decays.

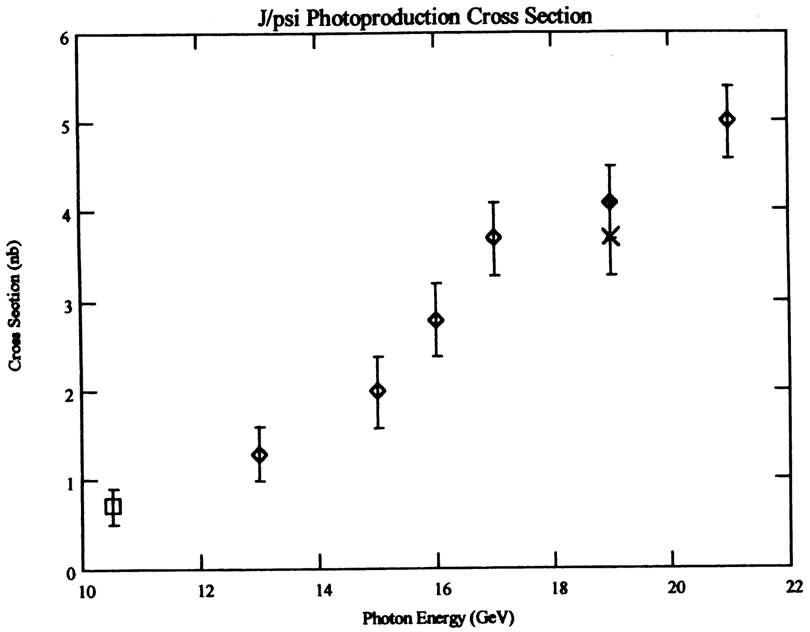

Figure 10 J/ψ photo-production cross sections (near threshold):

□ Cornell measurement
◇ SLAC deuterium measurement
× SLAC hydrogen measurement

Count Rate

The J/ψ photo-production cross section is quite small, hence high luminosity is required to obtain a reasonable count rate. The near threshold cross sections measurements are shown in Figure 10 [23][24]. The lowest energy measurement, by the Cornell group, had a range in photon energy between 9 and 11.8 GeV and did not see any signification energy dependence. Therefore, the cross section at threshold is assumed to be ~ 0.5 nb for the count rate estimation. All the assumptions used to calculate the count rate are in Table 1 At this point, the efficiency which corrects for μ's lost in the Fe and applied cuts, is an approximation. More detailed Monte Carlo studies are needed to accurately determine this quantity. Table 2 shows the number of detected J/ψ events per day and the equivalent uniform radius for each nuclei.

Table 1 Count Rate Assumptions

$\sigma_{\gamma J/\psi}$		0.5 nb
# γ/e-		0.1 %
Beam Current		80 μAmps
Solid Angle		2π
μ+μ- Branching Ratio		6.9 %
High P_{Fermi} Nucleons		1 %
Efficiency		50 %
# nucleons per 10 % Rad.Len. ($\times10^{24}$)	C	2.57
	Cu	0.77
	Au	0.39

Table 2 J/ψ events per day for various nuclei

Target	Equivalent uniform radius	# J/ψ events per day
C	3.2 fm	3600
Cu	5.0 fm	1100
Au	6.9 fm	500

Summary

This experiment will measure the nuclear dependence of J/ψ photo-production at threshold and will extract the physical J/ψ-N cross section. The rather simple experimental setup allows the measurement of the small J/ψ signal via the clean tagging of the $\mu^+\mu^-$ decay products. Based on the experience of the previous SLAC experiment, we would need (for an estimated final statistical uncertainty in $\sigma_{J/\psi N}$ of 10 %) about five days per target.

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